Flight Test Results of the Earth Observing-1 Advanced Land Imager

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ABSTRACT

The Advanced Land Imager (ALI) is the primary instrument on the Earth Observing-1 spacecraft (EO-1) and was developed under NASA's New Millennium Program (NMP). The NMP mission objective is to flight-validate advanced technologies that will enable dramatic improvements in performance, cost, mass, and schedule for future, Landsat-like, Earth Science Enterprise instruments. ALI contains a number of innovative features designed to achieve this objective. These include the basic instrument architecture, which employs a push-broom data collection mode, a wide field-of-view optical design, compact multi-spectral detector arrays, non-cryogenic HgCdTe for the short wave infrared bands, silicon carbide optics, and a multi-level solar calibration technique. The sensor includes detector arrays that operate in ten bands, one panchromatic, six VNIR and three SWIR, spanning the range from 0.433 to 2.35 μm. Launched on November 21, 2000, ALI instrument performance was monitored during its first year on orbit using data collected during solar, lunar, stellar, and earth observations. This paper will provide an overview of EO-1 mission activities during this period. Additionally, the on-orbit spatial and radiometric performance of the instrument will be compared to pre-flight measurements and the temporal stability of ALI will be presented.

Keywords: EO-1, ALI, MTF, calibration, performance assessment.

1. INTRODUCTION

The primary goal of the Advanced Land Imager is to flight-validate emerging technologies so that they may be integrated into future Earth-observing instruments for a substantial mass, power, and cost savings, while acquiring high-quality data. The key technologies being tested on the ALI include large, wide field-of-view silicon carbide optics, compact multispectral arrays, non-cryogenic (220 K) HgCdTe detectors, and a novel solar calibration technique. The validation of these technologies hinges on flight data that is accurately calibrated and free of distortion. Launched on November 21, 2000, the ALI collected several calibration data sets during the first year of operations on-orbit in order to verify the performance of the instrument. This paper provides an overview of the on-orbit spatial and radiometric performance assessment of the ALI based on these data and compares results with those obtained during preflight calibration.

2. INSTRUMENT OVERVIEW

A conceptual sketch of the interior of the ALI illustrating the major design features is shown in Figure 1. The telescope is an f/7.5 reflective triplet design with a 12.5 cm unobscured entrance pupil and a 15° cross-track by 1.25° in-track field-of-view. It employs reflecting optics throughout, to cover the fullest possible spectral range. The telescope design incorporates silicon carbide mirrors and an Invar truss structure with appropriate mounting and attachment fittings. The optical design features a flat focal plane and telecentric performance, which greatly simplifies the placement of the filter and detector array assemblies.

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Although the optical system supports a 15° wide field-of-view, only 3° (37 km cross-track) was populated with detector arrays for the technology demonstration. If the focal plane were fully populated, the detector arrays would cover an entire 185 km swath on the ground, equivalent to Landsat, in a 'push-broom' mode. The multispectral panchromatic (MS/Pan) array has 10 spectral bands in the visible, near infrared (VNIR), and short wave infrared (SWIR) (Table 1). Six of the nine multispectral bands are the same as those of the Enhanced Thematic Mapper (ETM+) on Landsat 7 for direct comparison. The additional bands, indicated with primes, were chosen for other science objectives.

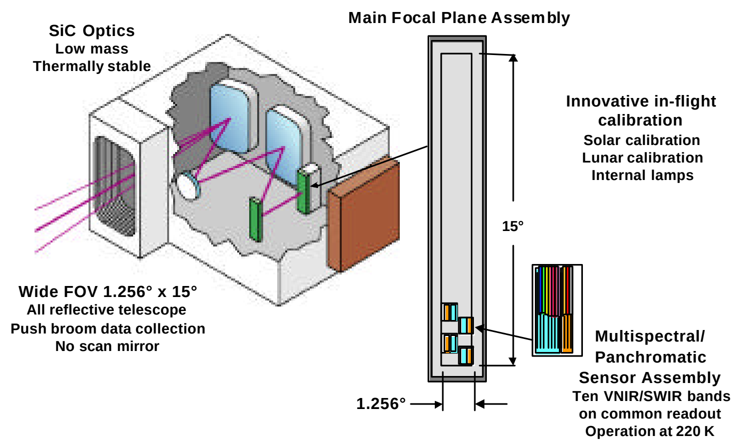

Figure 1. A conceptual sketch of the ALI telescope and Focal Plane Assembly.

Band	Wavelength (µm)	GSD (m)
Pan	0.480-0.690	10
MS-1'	0.433-0.453	30
MS-1	0.450-0.515	30
MS-2	0.525-0.605	30
MS-3	0.630-0.690	30
MS-4	0.775-0.805	30
MS-4'	0.845-0.890	30
MS-5'	1.200-1.300	30
MS-5	1.550-1.750	30
MS-7	2.080-2.350	30

Table 1. ALI Spectral Coverage and Ground Sample Distances

3. ON-ORBIT CHARACTERIZATION AND CALIBRATION

A variety of data was collected during the first year of operations on-orbit in order to verify the performance of the instrument. Spatial calibration data included observations of stars, the Moon, bridges, and center-pivot crop fields. Data were collected over all four SCAs, in order to sample the instrument modulation transfer function across the field of view. Radiometric calibration data include observations of the Sun, Moon, stars, ground calibration targets, and internal reference lamps. These data were collected over the entire field of view in an effort to provide accurate calibration data for each detector.

3.1 Imaging Performance

Flight data indicate the spatial performance of the ALI is nominal. Figure 2 depicts a 7,4,2 false color image of New Zealand. Figure 3 depicts a portion of a colorized panchromatic image of Pearl Harbor.

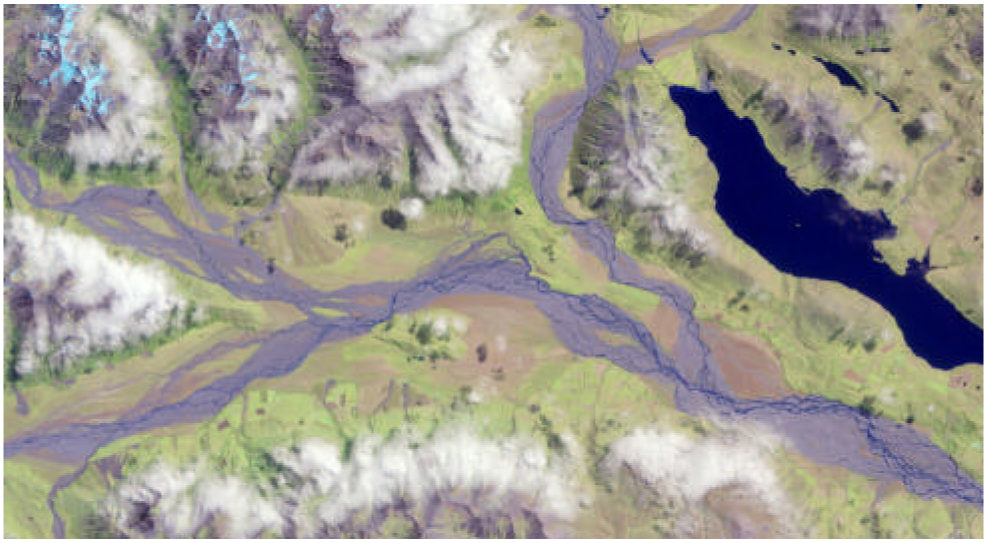

Figure 2. False-color multispectral image of part of the South Island of New Zealand. Multispectral bands 7, 4, and 2 were used to create this image. Ground sample distance is 30 meters.

Figure 3: Colorized panchromatic image of the Honolulu airport near Pearl Harbor, HI. Ground sample distance is 10 meters.

3.2 Modulation Transfer Function

The modulation transfer function (MTF) was extensively calibrated at Lincoln Laboratory before integration with the spacecraft and is discussed elsewhere[2]. The on-orbit approach to validating the MTF is to use the spatial calibration data to simulate the instrument response to simple models of certain well-defined objects imaged from space. The simulated response is then compared to the actual response. If the two match well, the MTF is validated.

Objects that have been used to date for MTF validation are bridges, the Moon, and stars. Bridges can provide a roughly uniform strip of radiance contrasting with the uniform darker water on either side. The lunar limb presents a sharp edge against dark space. Bright stars are essentially point sources that yield the instrument's point-spread function, albeit at a low sampling frequency.

An example of a bridge scan is shown in left half of Figure 4. It is the Bronx Whitestone Bridge, seen in a scan of New York City on March 20, 2001. The dotted rectangle delineates the pixels we used to test the MTF of the ALI. Those pixels were projected onto an axis perpendicular to the bridge. The result is shown in the right half of Figure 4. The radiance along that axis was modeled as a step function, including the bridge, the water on each side, and the shadow of the bridge on the water. The expected system response to this model was computed using the modulation transfer function from our laboratory calibration. The resulting fitted response is shown in red. The close agreement between the fitted response and the pixel data indicates the validity of the calibrated MTF.

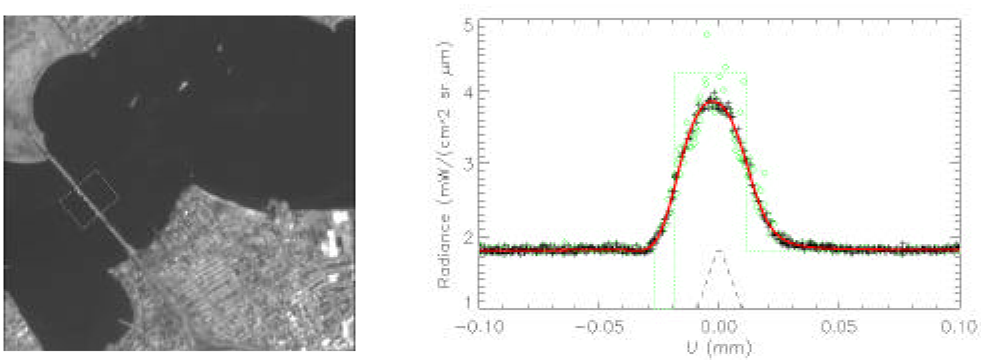

Figure 4. Portion of the panchromatic image of New York City, scanned on March 20, 2001.

A panchromatic image from a lunar calibration scan is seen in Figure 5. A small region of interest (ROI) along the southwest limb was selected. As for the bridge image, the pixel radiances in the ROI were projected onto an axis perpendicular to the limb. The result is shown on the right in Figure 5. The figure also shows the panchromatic edge spread function computed from the MTF calibration data. Apart from a fall-off of lunar radiance inward from the limb, the agreement is close. In particular, the slope of the edge spread function matches the radiance data very well.

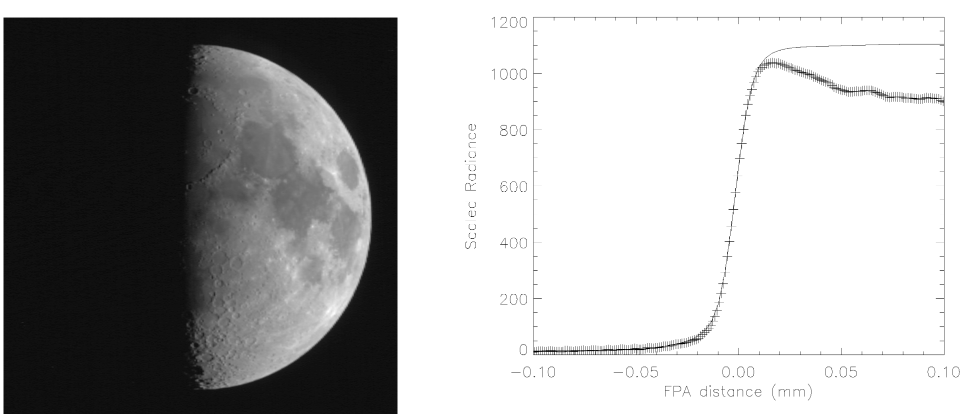

Figure 5. Lunar calibration data used to validate ALI MTF. On the right, the scaled panchromatic radiance of the lunar limb as a function of distance perpendicular to the limb in the focal plane space is provided. The crosses are the averaged data within the ROI, and the smooth curve is the computed ALI edge spread function.

A scan with SCA 4 across the 0.3 magnitude star Vega was conducted on May 15, 2001. The scan was performed at one-fourth the nominal angular image speed of earth scenes. Thus the data are sampled four times per detector height in the scan direction. Figure 6 shows the panchromatic radiance profiles through the star in the in-scan and cross-scan directions. The crosses are the calibrated scan data, and the curves represent the point-spread function computed from the MTF calibrations and fitted to the scan data. In the case of the Vega scan, we observe from Figure 6 that the instrument performance may be better than indicated by the laboratory calibrations.

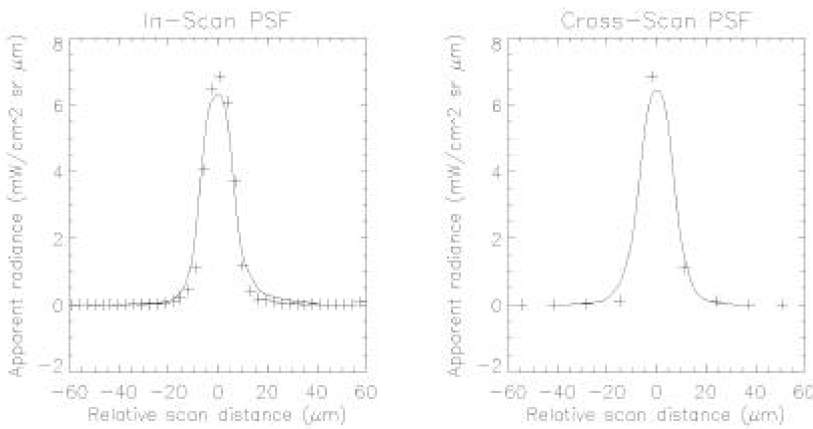

Figure 6. Panchromatic radiance profiles of Vega in the in-scan (left) and cross-scan directions. Only one row or column of pixels through the center of the star's image is shown in each case (crosses). The curve is a fitted Pan point-spread function.

3.3 Radiometric Performance

The radiometric response of the ALI is a function that is applied to each detector in order to transform the digital response of the instrument (DN) into scientific units (e.g. $mW/cm^2/sr/\mu m$). The usefulness of a response function is based on its accuracy, when comparing calibrated instrument data to scenes with independently known radiances. The radiometric response of the ALI was extensively calibrated at Lincoln Laboratory before integration with the spacecraft and is discussed elsewhere[3]. The response of the instrument was also calculated on orbit using data from four independent calibration sources: solar, lunar, ground truth, and internal reference lamps. These data are used to determine if any changes in the response of the instrument occurred during integration and testing at the spacecraft level or during launch as well as monitor the instrument's stability on orbit.

3.3.1 Solar Calibration

Solar calibration of the ALI is conducted approximately every fourteen days. The solar calibration procedure, which is illustrated in Figure 7, involves pointing the ALI at the Sun with the aperture cover closed. A motor-driven aperture selector in the aperture cover assembly moves an opaque slide over a row of small to increasingly larger slit openings and then reverses the slide motion to block all sunlight. Just prior to solar calibration, a space grade Spectralon® diffuser plate is swung over the secondary mirror by a motor-driven mechanism. The diffuser reflectively scatters the sunlight that would otherwise impinge on the secondary mirror. The scattered sunlight exposes the FPA to irradiance levels equivalent to earth-reflected sunlight for albedos ranging from 0 to 100%.

The detector response during a solar calibration sequence consists of an approximately linear increase as the aperture opens with a series of constant responses during those times when the edge of the slide passes over a reference bar. These bars provide a set of seven calibrated response points. When the aperture cover reverses direction and closes, the pattern of response reverses and proceeds back down to zero. The flux level at the maximum or seventh level corresponds approximately to a 100% albedo at a 30º solar zenith angle. Finally, the absolute radiometric calibration of the ALI, derived from pre-flight measurements, is checked by comparing the expected radiance observed for level 6 of the solar calibration to the observed radiance.

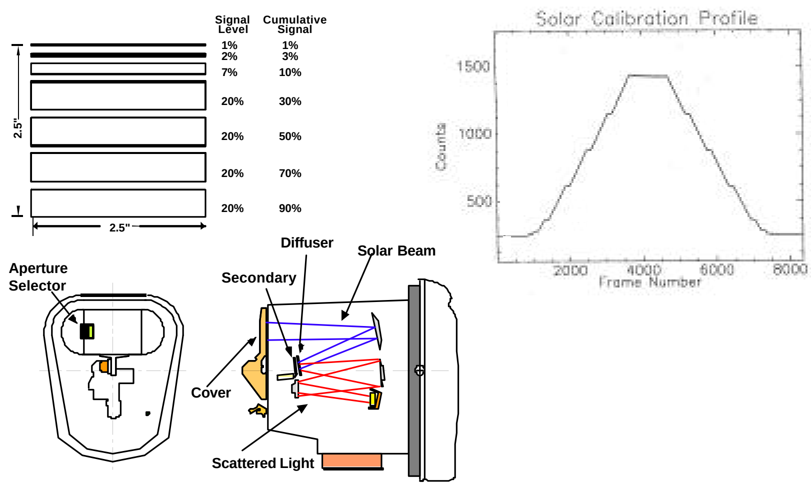

Figure 7. Illustration of the solar calibration mode and laboratory test data from a solar simulator.

3.3.2 Ground Truth

The second method of assessing the radiometric accuracy of ALI data hinges on reflectance-based ground truth measurements. This principle of this technique is to image a stable, high-altitude, flat, diffuse ground target using the ALI while ground teams simultaneously measuring the reflective properties of the target region and local atmospheric conditions. The ground measurements can then be used to predict the top of the atmosphere radiance observed by the ALI.

Throughout the first year of the EO-1 mission, ground truth campaigns were conducted by several groups, including the University of Arizona, the University of Colorado, the Australian CSIRO, and the NASA Jet Propulsion Laboratory. Ground truth sites include Barreal Blanco and Arizario Argentina, Lake Frome Australia, and complementary sites in the western United States (Railroad Valley, Ivanpah Playa, Walnut Gulch, and White Sands).

3.3.3 Lunar Calibration

A third method used to evaluate the absolute radiometry of the ALI on orbit is lunar calibration. This method involves observing the Moon with the instrument and comparing the measured lunar irradiance with a predicted lunar irradiance for the time of the observation.

Lunar observations using the ALI have been conducted near a 7° phase angle each month since January 2001. For each observation, the spacecraft is maneuvered to scan the Moon in the in-track direction at 1/8 the nominal scan rate in order to oversample the disk. To calculate the observed lunar irradiance, dark current levels are subtracted and the image is radiometrically calibrated using the pre-flight calibration coefficients. A region of interest, narrowly circumscribing the Moon, is then defined by locating the region of each column where the intensity falls to below 1% of the average lunar irradiance (Figure 8). Summing the response within the circumscribed region, the spectral irradiance of the Moon for each band may be calculated as

$$\AA_M(\ddot{e}) = \frac{d\Theta\Delta}{fF}\Sigma L_P(\,l\,)$$

Here, E_M (λ) is the lunar spectral irradiance, $d\Theta$ is the ALI pitch rate during the scan (radians/second), Δ is the detector pitch (μm), f is the ALI focal length (m), F is the frame rate (Hz), and L_P (λ) is the measured lunar spectral radiance for detector P (mW/cm^2/sr/μm).

Figure 8. Image of the Moon taken by the ALI on February 7, 2001. The circle surrounding the Moon describes the regions used in the lunar irradiance calculations.

Once the measured lunar irradiance has been calculated for a given observation, the expected lunar irradiance for the time of the observation is calculated by the USGS using data obtained from the robotic lunar observatory (ROLO) in Flagstaff Arizona[5]. Since 1996, ROLO has been measuring the lunar irradiance between 350 and 2500 nm as a function of phase angle as often as weather and seeing permit. The USGS has been able to use this database to predict lunar irradiances for most phase angles. As a result, lunar observations are emerging as an exciting new opportunity for radiometric calibration of space based VNIR/SWIR instruments.

In order to investigate the stability of the ALI over time using lunar calibration data, additional correction factors are applied to the irradiance data. These factors account for the varying distance between the Sun and Moon as a result of the Earth's revolution about the Sun and the Moon's revolution about the Earth, the instrument-Moon distance based on the spacecraft's orbit and the non-circular orbit of the Moon, and the lunar illumination fraction and brightness, which are both functions of the lunar phase.

3.3.4 Internal Reference Lamp Illumination

Another source of on-orbit radiometric calibration for the ALI is an internal reference source mounted on the inside of the optical metering truss. This source consists of three Welch Allyn 997418-7 (modified) gas-filled lamps mounted on a small (2.03 cm) diameter integrating sphere (Figure 9). Light emerging from the exit port of the sphere passes through a BK 7 lens and spectral-balancing filter, is reflected off the ALI flat mirror (M4), and floods the focal plane.

The internal reference lamps are activated during two data collection events per day, when the ALI aperture cover is closed. After an eight-second stabilization period the lamps are sequentially powered down in a staircase fashion, with two-second exposures between each step. In this manner, the focal plane will receive a daily three point radiometric reference.

Initially, the internal reference source was to serve as a radiometric transfer standard between pre-flight and on-orbit calibrations of the ALI. However, a noticeable increase in lamp output in the VNIR was observed immediately after launch. This has been attributed to a loss of convective cooling of the filament in the zero-G environment. This increase in lamp output has resulted in invalidating attempts at using the reference lamps as a calibration transfer standard between preflight and flight calibration of the ALI detector arrays. However, the lamp output has been very repeatable since launch and has proven to be invaluable at monitoring the stability of the focal plane during the first year of on-orbit operations.

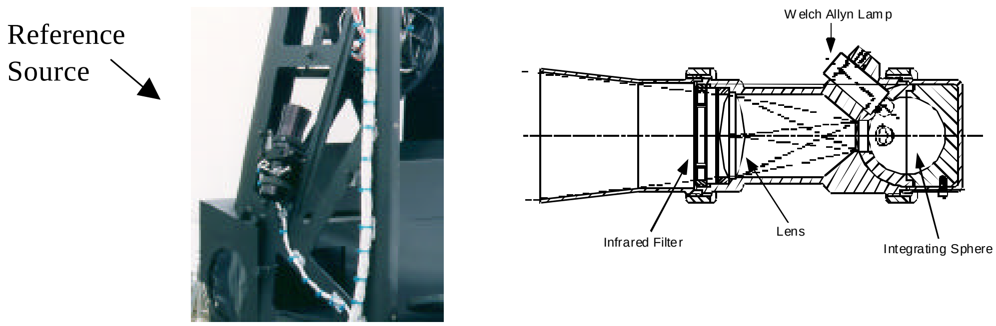

Figure 9. EO-1 ALI internal reference source.

3.3.5 Results

The measured solar calibration radiance for aperture selector position six have been normalized to the expected values and are presented in Fig. 10. These data are plotted at the mean wavelength of each band. With the exception of band 1p, the solar and pre-launch calibrations agree to within the estimated uncertainties of the two independent techniques. The pre-launch calibration accuracy combined with the additional on-orbit effects of contamination and stray light[3] is currently estimated to be less than 5% for all bands. The solar calibration uncertainty is currently estimated to be 5% in the VNIR bands and 7% in the SWIR bands. The larger uncertainty in the SWIR bands is due to both the uncertainty in the solar irradiance models and the BRDF of the Spectralon. The low response in band 1p is a significant discrepancy between the two calibration techniques.

Ground truth measurements of Barreal Blanco, Argentina and Ivanpah Playa, California obtained by the Remote Sensing Group of the University of Arizona are also presented in Figure 10. The errors associated with the ground truth measurements[4] have been estimated to be ±3%.

Clearly, the ground truth and solar calibration measurements agree for most bands. The repeatability of the Band 1p offset and overall trend in the VNIR add confidence to the solar calibration model and indicates a change in the ALI radiometric response since pre-flight calibration for these bands. However, a 7% difference between the solar and ground truth data exists for Band 5 and is not well understood at this time.

The results of a lunar irradiance comparison for measurements obtained on February 7, 2001 required a normalization of 5% to the ROLO data for all bands in order to bring the results into agreement with ALI measurements. The source of this offset is unclear at this time and is continuing to be investigated. However, once the 5% offset is applied, the lunar irradiance comparison result was overlaid with solar and ground truth comparisons in Figure 10. The lunar data agree well with the other techniques, supporting the hypothesis that the radiometric response of the instrument has changed significantly for Band 1p and has drooped slightly in the VNIR since pre-flight measurements were taken.

Extensive investigations into the discrepancy between preflight and flight radiometric response measurements have been conducted at the Laboratory and the most likely sources of these effects are changes in the reflectivities of the mirrors or bandpasses of the spectral filters. Contamination of the top surface of the focal plane filters has plagued the ALI since initial instrument thermal vacuum testing. Trending of internal lamp data indicate that a gradual build-up of material occurs when the focal plane is operated below 250 K. This data also reveals that the contaminant is virtually removed by raising the temperature of the focal plane for a 20-hour period every ten days on orbit. This chronic problem raises suspicions relating to the apparent permanent change in instrument response since preflight calibration. However, internal reference lamp trending indicates the reflectivity of flat mirror (M4) and the response of the focal plane has remained stable to within 1% for bands 1p, 1, 2, 5p, 5, 7, pan, and within 3% for bands 3, 4, 4p since launch. Unfortunately, the observed increase in internal lamp intensity after launch prohibits one from extending focal plane response trending from preflight calibration to on orbit. However, trending does exist from preflight calibration at Lincoln Laboratory in December 1998 through the second spacecraft thermal

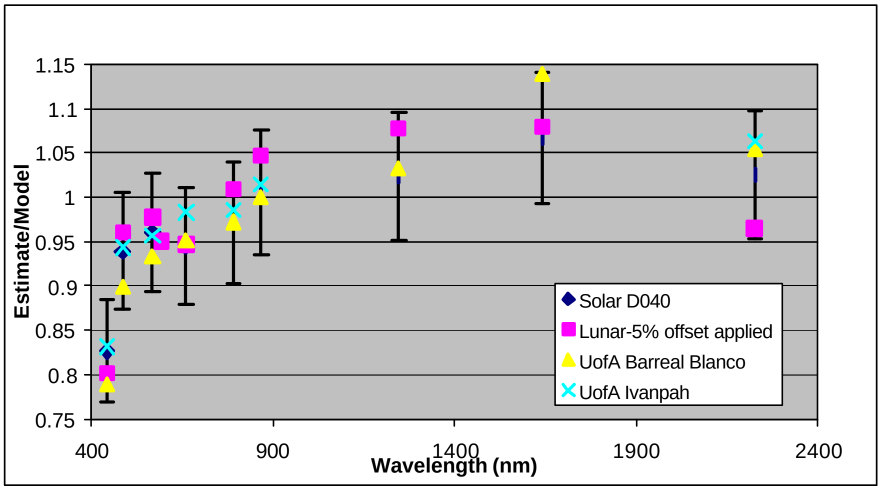

Figure 10: Results from solar, ground truth, and lunar absolute radiometric calibrations.

vacuum test at Goddard Space Flight Center in July 2000 (4 months before launch). This data indicates M4 and the focal plane have remained stable to within 2% during ground testing. Furthermore, solar, lunar, and ground truth data trending, which exercise other elements of the optical train, suggest M1, M2, M3, and the solar diffuser have been stable to within 1% since the first calibrations in late December 2000. As a result, if a response change did occur within the instrument, it must be restricted to between July 2000 and November 21, 2000 if the change occurred on M4 or the focal plane or it must be restricted to between December 1998 and December 29, 2000 if the change occurred on M1, M2, or M3.

3.3.6 Radiometric Stability

The radiometric stability of the ALI has been tracked since launch using the techniques outlined above. Solar calibrations occur every two weeks and began on January 9, 2001. Lunar calibrations occur monthly and began on January 28, 2001. Ground truth measurements occur approximately every 2 months and began on December 29, 2000. Internal reference lamp measurements have been taken daily since November 25, 2000. However, only internal lamp measurements taken one day after focal plane bakeouts are used in stability analyses.

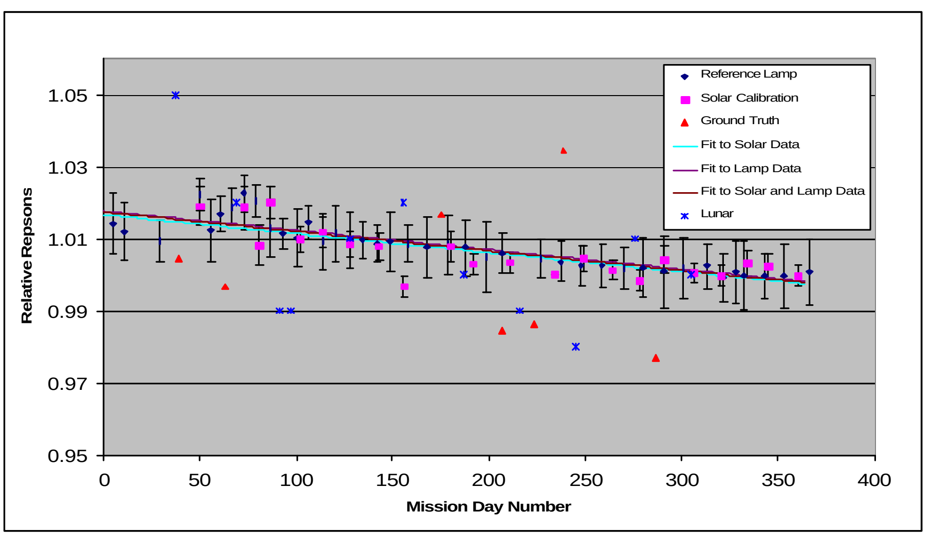

Figure 11: Radiometric stability for Band 3 during the first year on orbit.

The stability data from all of the techniques described above for Band 3 have been overlaid in Figure 11 as an example. Stability data indicate the instrument has been stable to within 1% for Bands 1p, 1, 2, 5p, 5, 7, pan and within 3% for Bands 3, 4, 4p since launch. Linear fits to the solar and internal lamp data are also overlaid. Table 2 tabulates stability results for each band.

Although the cause of the preflight to flight radiometric calibration discrepancy is not clearly understood, good agreement between solar, lunar and ground truth measurements, and excellent stability of the instrument suggests a single radiometric correction to the preflight calibration coefficients for each band will provide ±5% agreement between measured solar, lunar and ground truth data and expected values (Table 3). These factors have been used to update the preflight radiometric coefficients residing in the EO-1 ALI Radiometric Calibration Pipeline.

Band	Response Change (%/year)
1p	-0.8
1	-0.7
2	-0.9
3	-2.5
4	-2.6
4p	-2.7
5p	-0.8
5	-0.8
7	-0.7
Pan	-0.8

Table 2. Radiometric stability trending.

Band	Correction Factor
1p	1.21
1	1.07
2	1.05
3	1.04
4	1.02
4p	0.99
5p	0.98
5	0.87
7	0.98
Pan	1.05

Table 3. Radiometric correction factors.

4. SUMMARY

Flight data collected during the first year of operation on orbit indicate the ALI is healthy and functioning nominally. Calibration imagery indicates the instrument's spatial performance meets or exceeds expectations. An apparent change in the instrument radiometric response, particularly below 500 nm, between preflight calibration and on-orbit operations was consistently observed by solar, lunar, and ground truth data. Repeated radiometric calibration measurements also indicate the instrument stability is excellent and may be easily trended using linear functions. This allows for a single correction for each band in the calibration pipeline in order to bring the absolute radiometry of the ALI to within ±5%.

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